

# String completion of an $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ electroweak model

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The extended electroweak  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  symmetry framework “explaining” the number of fermion families is revisited. While 331-based schemes can not easily be unified within the conventional field theory sense, we show how to do it within an approach based on D-branes and (un)oriented open strings, on Calabi-Yau singularities. We show how the theory can be UV-completed in a quiver setup, free of gauge and string anomalies. Lepton and baryon numbers are perturbatively conserved, so neutrinos are Dirac-type, and their lightness results from a novel TeV scale seesaw mechanism. Dynamical violation of baryon number by exotic instantons could induce neutron-antineutron oscillations, with proton decay and other dangerous R-parity violating processes strictly forbidden.

Keywords: Unification, branes, string phenomenology, neutrino mass, neutron-antineutron oscillations

## I. INTRODUCTION

Among the open challenges in the standard model we encounter issues like: Why we have three species of fermions? Why the neutrino masses are so small? Why fundamental couplings unify? How is gravity incorporated in a fundamental way? One of the early extended electroweak models based on the  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  gauge group [1, 2] “explains” the number of fermion families from the requirement of anomaly cancellation. Indeed the theory is anomaly free if and only if the number of quark colors is equal to the number of families, i.e. three (species of fermions) is related to quantum consistency [1–7]. Recently this scenario has been revamped in order to also provide a framework for naturally light neutrinos without invoking superheavy physics [8]. In this scheme these two fundamental issues get related through the embedding of the standard model gauge group in  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ . In the simplest 3-3-1 model considered recently neutrino masses were radiatively generated by one-loop corrections, involving new neutral gauge bosons associated to lepton number violating interactions [8]. Within a simple variant it has been shown that the same physics involved in small neutrino mass generation may also achieve gauge coupling unification [9], alternative to conventional grand unified theories.

A drawback of such  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  based-models is, however, that they cannot be easily embedded in a conventional Grand Unified Theory (GUT). In order to achieve gauge coupling

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unification the authors in Ref. [9] considered an alternative more complicated version of the model, in which the presence of a neutral sequential lepton octet allowed for the merging of the gauge couplings at high energies in the absence of a *bona fide* grand-unified structure. A more ambitious theoretical question is whether such a structure could be UV-completed and understood in more fundamental terms.

Here we show that our desire of obtaining a consistent string completion of this type of 3-3-1 theories leads us to the novel variety of seesaw mechanism proposed in [10], in which neutrinos are Dirac particles with masses generated at the tree level. Moreover, we find that neutrino masses vanish in the limit where the up-quark mass vanish. As a result, consistency of the neutrino sector with the observed quark masses suggests that the new dynamics associated with neutrino mass generation must reside near the TeV scale. On this basis we expect that this model can be directly tested at LHC in the next run, through the resonant production of new fields involved in the neutrino mass generation mechanism. In particular, a new  $Z'$  boson can be produced through the Drell-Yan processes. This boson couples to standard model particles and to the new isosinglet neutral leptons [11]. Another interesting indirect signature predicted by this model is  $b \rightarrow s\mu^+\mu^-$ , gauge mediated by the new  $Z'$  boson [12]. Likewise, there are also lepton flavour violation signals, recently investigated in a simple variant of these models [13].

## II. STRING CONSIDERATIONS

In this paper, we show how a  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  model can be embedded into an open string theory. In particular, we will show how this model can be obtained by a system of intersecting D-branes and open (un)oriented strings attached to D-branes. The open string models <sup>1</sup> that can realistically embed standard model -like theories or their extensions can be divided into three classes: i) (un)oriented type IIA, with intersecting D6-branes wrapping 3-cycles on the Calabi-Yau compactification  $CY_3$ ; ii) (un)oriented type IIB, with D7-branes and D3-branes wrapping holomorphic divisors in  $CY_3$ . iii) type I, with magnetized D9-branes wrapping a  $CY_3$ . Here we will focus on the first class. In this case, we can directly calculate low energy interactions for  $\alpha_s \rightarrow 0$ , obtaining just an  $\mathcal{N} = 1$  supergravity coupled with matter fields. In particular, we will discuss a simple example of a “quiver field theory” embedding of  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  locally free of stringy anomalies or tadpoles.

In general, a “quiver” is simply a diagrammatic representation of a gauge theory. A supersymmetric quiver (as in our case) includes all the matter (super)field content, represented with arrows, and their interactions. The corresponding diagrams have the following conventions <sup>2</sup>: i) gauge groups are nodes, which are in correspondence with the gauge superfields; ii) superfields are oriented lines between nodes; iii) superfields in the adjoint representations are arrows going in and out on the same node; those in the bi-fundamental representations  $(\mathbf{M}, \bar{\mathbf{P}})$  or  $(\bar{\mathbf{M}}, \mathbf{P})$  link two different nodes/gauge groups; iv) the number of arrows on a line corresponds to the multiplicity of the same superfield; v) Closed oriented paths (arrows with the same orientation) like triangles, quadrangles, and so on, represent possible gauge-invariant interaction terms in the superpotential.

In open string theories, quiver diagrams are particularly powerful. This is because D-brane dynamics

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<sup>1</sup> For general aspects open-strings theories see [14–20].

<sup>2</sup> See [21] for a useful papers on (un)oriented quivers’ technology.

on Calabi-Yau singularities is described by quiver field theories in the low energy limit  $\alpha_s \rightarrow 0$ . In string theory, lines connecting nodes correspond to (un)oriented open strings, while nodes are D-brane stacks. Intriguingly, we will show how the quiver field theory suggests the existence of novel phenomena characteristically “stringy” in nature. In particular, we will see how the presence of new anomalous massive bosons is inevitably predicted. In gauge theories, anomalous U(1)s lead to quantum inconsistencies, but in string theories these can be cured through a Generalized Green-Schwarz mechanism (GGS) and Generalized Chern Simon terms. As a result, anomaly cancellation implies mixing vertices connecting the  $\gamma, Z, Z', X$  gauge bosons with those of the anomalous U(1)s [22–24].

There are other interesting features of quiver field theories related to non-perturbative stringy effects which could manifest at low energies. For example, at the low energy limit, a quiver field theory admits the presence of extra non-perturbative couplings in the effective action, generated by “exotic stringy instantons”.

All gauge instantons are classified by the Atiyah, Drinfeld, Hitchin, Manin (ADHM) construction. In (un-)oriented type IIA, gauge instantons can be described by Euclidean D2 branes (or E2 branes) wrapping the *same* 3-cycles of “ordinary physical” D6-branes on the Calabi-Yau  $CY_3$  [25, 26]. In (un-)oriented IIB, E-instantons are E3-branes or E(-1)-branes wrapping the same holomorphic divisor of “ordinary physical” D7-branes. Furthermore, in type I, E-instantons are E5 branes living in the internal space and having the same magnetization of the physical D9-branes. (D9-branes wrap on all the  $CY_3$ ). However, in string theory there is another large class of new instantons defined as “exotic”. They do not exist in gauge theories, and do not need to satisfy ADHM constraints. In type IIA, exotic instantons are simply E2-branes wrapping *different* 3-cycles from ordinary physical D6-branes. More precisely, exotic instantons have 8 mixed Neumann-Dirichlet directions, in contrast to the 4 mixed directions of the D6/D2 case, which admits an ADHM construction. In general, stringy instantons lack bosonic zero-modes in the mixed sector. Thus, upon integration over the charged Grassmannian moduli, their contribution to the superpotential gives rise to positive powers of the fields, opposite with respect to the behavior of standard gauge instantons.

In quiver field theories, E-brane instantons are represented as triangles. Open strings attached to one ordinary D-brane and one E-brane are fermionic moduli or modulini, corresponding to ‘dotted’ arrows. Closed triangles of lines and dotted lines correspond to effective interactions among ordinary fields and modulini. Integrating out moduli, new effective interactions among ordinary fields are generated. As shown in [27–39], these new interactions can dynamically violate Baryon and Lepton numbers. Indeed, we will discuss how exotic instantons can directly generate  $\Delta B = 2$  six quarks transitions generating neutron-antineutron oscillations. However, even if  $B$  number is violated in our model, the selection rule  $\Delta B = 2$  emerges dynamically, so that proton stability and R parity conservation are ensured.

### III. UN-ORIENTED QUIVER THEORY FOR A $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ MODEL

#### A. Setup

In this section we describe the basic ingredients of our model, diagrammatically represented as the quiver in Fig. 1. This quiver generates a  $\mathcal{N} = 1$  supersymmetric theory with gauge group

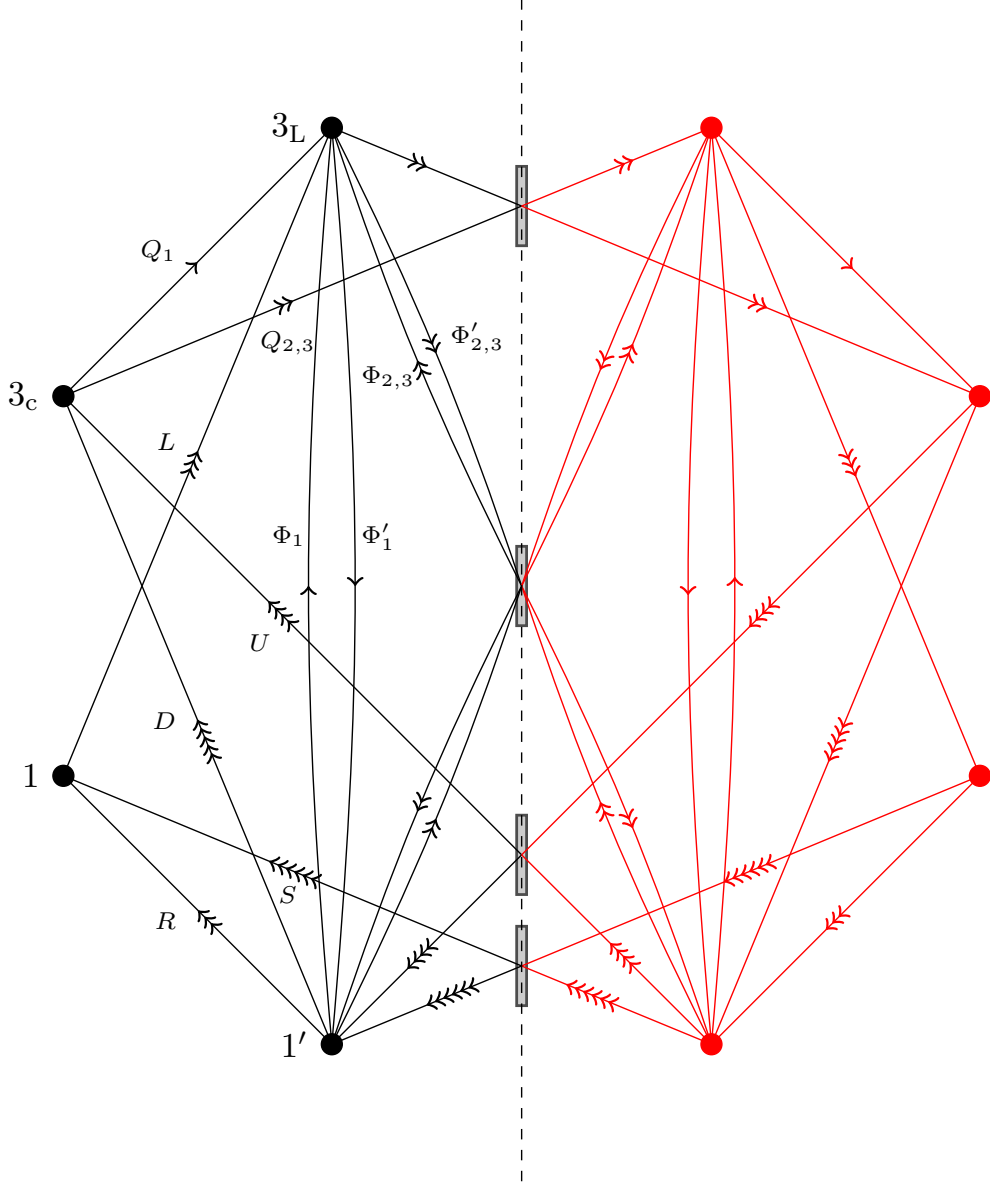


FIG. 1:  $U(3)_c \otimes U(3)_L \otimes U(1) \otimes U(1)'$  (un)oriented quiver theory, in the presence of a  $\Omega$ -plane.

$U(3)_c \otimes U(3)_L \otimes U(1) \otimes U(1)'$ , containing a  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X \equiv G_{331}$  model. The matter content and the (super)field transformation properties under  $(SU(3)_c, SU(3)_L)_X$  are

$$\begin{aligned}
 L_{1,2,3} &= (1, \bar{3})_{-1/3}, & Q_1 &= (3, \bar{3})_{1/3}, & Q_{2,3} &= (3, 3)_0, \\
 R_{1,2,3} &= (1, 1)_1, & U_{1\dots 4} &= (\bar{3}, 1)_{-2/3}, & D_{1\dots 5} &= (\bar{3}, 1)_{1/3}, & S_{1\dots 6} &= (1, 1)_0, \\
 \Phi_1 &= (1, \bar{3})_{2/3}, & \Phi_{2,3} &= (1, \bar{3})_{-1/3}, & \Phi'_1 &= (1, 3)_{-2/3}, & \Phi'_{2,3} &= (1, 3)_{1/3}.
 \end{aligned} \tag{1}$$

Here  $L_i$  ( $i = 1, 2, 3$ ) accommodates the  $SU(2)_L$  lepton doublets  $\ell_i = (E_L, \nu_L)_i^T$  together with new neutral components  $N_{L_i}$  into the anti-triplet representation of  $U(3)_L$ ;  $Q_i$  includes the LH doublets  $q_i = (u_L, d_L)_i^T$  plus extra quark fields  $u'_L, s'_L, b'_L$ ;  $R$  stands for the right-handed charged lepton multiplets and  $U, D$  contain the right-handed quarks  $u_R, d_R$  plus extra three (super)quarks  $u'_R, s'_R, b'_R$ . In addition, there are six  $G_{331}$  singlets denoted by  $S$ , i.e. there is a pair of gauge singlets in each

generation. Finally, the scalar components of the Higgs superfields  $\Phi_{1,2,3}, \Phi'_{1,2,3}$  are responsible for the  $G_{331}$  spontaneous symmetry breaking.

The effective trilinear quark and lepton superpotentials, perturbatively generated, are given as

$$\begin{aligned} \mathcal{W}_{\text{leptons}} &= y_1 LR\Phi'_1 + y_2 LS\Phi'_2 + y_3 LS\Phi'_3, \\ \mathcal{W}_{\text{quarks}} &= y_4 Q_1 D\Phi'_1 + y_5 Q_1 U\Phi'_2 + y_6 Q_1 U\Phi'_3 + y_7 Q_{2,3} U\Phi_1 + y_8 Q_{2,3} D\Phi_2 + y_9 Q_{2,3} D\Phi_3. \end{aligned} \quad (2)$$

Each term corresponds to a closed oriented triangle following the arrows associated to chiral superfields depicted in Fig. 1. Moreover, one can see that R-parity violating terms like  $LQD$  are automatically forbidden at the perturbative level. This is related to the quiver orientations: *there are no closed oriented triangles corresponding to R-parity violating superpotential terms*. As a consequence, R-parity is not imposed *ad hoc* in our model, but appears as an *accidental* symmetry.

The first stage of gauge symmetry breaking pattern involves a Stueckelberg mechanism [40], while the latter is induced by scalar vacuum expectation values (VEVs) through the Higgs mechanism. The pattern is  $U(3)_c \otimes U(3)_L \otimes U(1) \otimes U(1)' \rightarrow SU(3)_c \otimes SU(3)_L \otimes U(1)_X \rightarrow G_{\text{SM}}$ . Note that the quiver also generates perturbatively the  $\mu$ -terms for the Higgs superfields, required for electroweak breaking

$$\mathcal{W}_\mu = \mu_1 \Phi_1 \Phi'_1 + \mu_2 \Phi_2 \Phi'_2 + \mu_3 \Phi_3 \Phi'_3 + \mu_4 \Phi_2 \Phi'_3 + \mu_5 \Phi_3 \Phi'_2. \quad (3)$$

These terms correspond to closed circuits involving Higgs superfields in Fig. 1. The proposed quiver can be interpreted as the UV completion of a particular  $G_{331}$  model with extra neutral leptons in the triplet representation. For recent studies in this class of models see for example Ref. [8] and [10, 13]. A remarkable feature of this quiver construction is that neutrinos are of Dirac nature, thanks to the presence of a (sequential) pair of lepton singlets  $S^3$  and to the symmetry structure of the model.

## B. Tadpole cancellation and $U(1)_X$ conditions

The quiver in Fig.1 preserves a linear combination  $U(1)_X = \sum_a C_a U(1)_a$ , with  $a = 3_c, 3_L, 1, 1'$  and  $U(1)_{3_c} \subset U(3)_c$ ,  $U(1)_{3_L} \subset U(3)_L$ ,  $U(1)_1 \equiv U(1)$ ,  $U(1)_{1'} \equiv U(1)'$ , that can be obtained from the following system:

$$\begin{aligned} X(Q_1) &= C_{3_c} - C_{3_L} = 1/3, & X(Q_{2,3}) &= C_{3_c} + C_{3_L} = 0, & X(L) &= -C_{3_L} + C_1 = -1/3, \\ X(U) &= -C_{3_c} - C_{1'} = -2/3, & X(D) &= -C_{3_c} + C_{1'} = 1/3, \\ X(R) &= -C_1 + C_{1'} = 1, & X(S) &= -C_1 - C_{1'} = 0, \\ X(\Phi_1) &= -X(\Phi'_1) = -C_{3_L} + C_{1'} = \frac{2}{3}, \\ X(\Phi_{2,3}) &= -X(\Phi'_{2,3}) = -C_{3_L} - C_{1'} = -\frac{1}{3}. \end{aligned} \quad (4)$$

Here we have adopted the convention  $+$  for outgoing arrows and  $-$  for incoming ones. The solution

$$U(1)_X = \frac{1}{6} U(1)_{3_c} - \frac{1}{6} U(1)_{3_L} - \frac{1}{2} U(1) + \frac{1}{2} U'(1). \quad (5)$$

corresponds to the defining symmetry of the  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  model [10].

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<sup>3</sup> The first feature resembles the assumption made in Ref. [41].

In order to describe a consistent model, the quiver must be free of chiral gauge and gravitational anomalies, with  $U(1)_X$  unbroken at the string level. These requirements are related to the fulfillment of two more stringent conditions. The first one is local tadpole cancellation [42–44]:

$$\sum_a N_a (\pi_a + \pi_{a'}) = 4\pi_\Omega, \quad (6)$$

where  $\pi_a$  denotes 3-cycles wrapped by “ordinary” D6-branes,  $\pi_{\hat{a}}$  stands for the corresponding 3-cycles wrapped by the “ $\Omega$ -image” D6-branes, and  $\pi_\Omega$  is the contribution of the  $\Omega$ -plane. More conveniently, Eq. (6) can be expressed in terms of superfields as

$$\forall a \neq a' \quad \#F_a - \#\bar{F}_a + (N_a + 4)(\#S_a - \#\bar{S}_a) + (N_a - 4)(\#A_a - \#\bar{A}_a) = 0, \quad (7)$$

with  $F_a, \bar{F}_a, S_a, \bar{S}_a, A_a, \bar{A}_a$  as fundamental, symmetric and antisymmetric representations of  $U(N_a)$  (together with their conjugates). Eqs.(6,7) are only locally equivalent, and they can not strictly be identified in a global analysis. In the following, we study only the local consistency conditions of our model. Notice that for  $N_a > 1$  the above relations coincide with the absence of irreducible  $SU(N_a)^3$  triangle anomalies [1]. The most important cases are those satisfying  $N_a = 1$ , and can be interpreted as stringy conditions related to the absence of ‘irreducible’  $U(1)^3$ , *i.e.* contributions that arise from diagrams with insertions of the same  $U(1)$  vector boson on the same boundary. The explicit tadpole cancellation follows from

$$\begin{aligned} U(3)_c : \quad & 3n_{Q_1} + 3n_{Q_{2,3}} - n_D - n_U = 3 + 6 - 5 - 4 = 0, \\ U(3)_L : \quad & 3n_{Q_{2,3}} - 3n_{Q_1} - n_L = 6 - 3 - 3 = 0, \\ U(1) : \quad & 3n_L - n_R - n_S = 9 - 3 - 6 = 0, \\ U(1)' : \quad & 3n_D - 3n_U + n_R - n_S = 15 - 12 + 3 - 6 = 0. \end{aligned} \quad (8)$$

The second important condition observed by the quiver field theory reads

$$\sum_a C_a N_a (\pi_a - \pi'_a) = 0, \quad (9)$$

and guarantees the existence of a massless vector boson associated with the unbroken  $U(1)_X = \sum_a C_a U(1)_a$  symmetry [42–44]. Again, in terms of field representations, Eq. (9) can be written as

$$C_a N_a (\#S_a - \#\bar{S}_a + \#A_a - \#\bar{A}_a) - \sum_{b \neq a} C_b N_b [\#(F_a, \bar{F}_b) - \#(F_a, F_b)] = 0, \quad (10)$$

and is satisfied by  $U(1)_X$  accordingly:

$$\begin{aligned} 3_c : \quad & -3C_{3_L} (n_{Q_1} - n_{Q_{2,3}}) - C_{1'} (-n_D + n_U) = \frac{1}{2}(1 - 2) - \frac{1}{2}(-5 + 4) = 0, \\ 3_L : \quad & -3C_{3_c} (-n_{Q_1} - n_{Q_{2,3}}) - C_1 (-n_L) = -\frac{1}{2}(-1 - 2) + \frac{1}{2}(-3) = 0, \\ 1 : \quad & -3C_{3_L} (n_L) - C_{1'} (-n_R + n_S) = \frac{1}{2}(3) - \frac{1}{2}(-3 + 6) = 0, \\ 1' : \quad & -3C_{3_c} (n_D + n_U) - C_1 (n_R + n_S) = -\frac{1}{2}(5 + 4) + \frac{1}{2}(3 + 6) = 0. \end{aligned} \quad (11)$$

We conclude this section pointing out that the remaining Abelian and mixed anomalies can be canceled by a Generalized Green-Schwarz mechanism with Stueckelberg, axionic and generalized Chern-Simons couplings, following the lines of [22–24]. This mechanism introduces non trivial interactions among the various gauge bosons of the model and provides potentially interesting phenomenological implications.

## IV. PHENOMENOLOGY

### A. Quark sector

Fermion masses are obtained perturbatively, after spontaneous breaking of the gauge symmetry, from the Yukawa interactions present in Eq. (2). For the quarks one has the following mass matrices

$$m_u = \frac{1}{\sqrt{2}} \begin{pmatrix} k'_2 y_5^{uu} + k'_3 y_6^{uu} & k'_2 y_5^{uc} + k'_3 y_6^{uc} & k'_2 y_5^{ut} + k'_3 y_6^{ut} & k'_2 y_5^{uu'} + k'_3 y_6^{uu'} \\ k_1 y_7^{cu} & k_1 y_7^{cc} & k_1 y_7^{ct} & k_1 y_7^{cu'} \\ k_1 y_7^{tu} & k_1 y_7^{tc} & k_1 y_7^{tt} & k_1 y_7^{tu'} \\ n'_2 y_5^{uu} + n'_3 y_6^{uu} & n'_2 y_5^{uc} + n'_3 y_6^{uc} & n'_2 y_5^{ut} + n'_3 y_6^{ut} & n'_2 y_5^{uu'} + n'_3 y_6^{uu'} \end{pmatrix}, \quad (12)$$

$$m_d = \frac{1}{\sqrt{2}} \begin{pmatrix} k'_1 y_4^{dd} & k'_1 y_4^{ds} & k'_1 y_4^{db} & k'_1 y_4^{ds'} & k'_1 y_4^{db'} \\ k_2 y_8^{sd} + k_3 y_9^{sd} & k_2 y_8^{ss} + k_3 y_9^{ss} & k_2 y_8^{sb} + k_3 y_9^{sb} & k_2 y_8^{ss'} + k_3 y_9^{ss'} & k_2 y_8^{sb'} + k_3 y_9^{sb'} \\ k_2 y_8^{bd} + k_3 y_9^{bd} & k_2 y_8^{bs} + k_3 y_9^{bs} & k_2 y_8^{bb} + k_3 y_9^{bb} & k_2 y_8^{bs'} + k_3 y_9^{bs'} & k_2 y_8^{bb'} + k_3 y_9^{bb'} \\ n_2 y_8^{sd} + n_3 y_9^{sd} & n_2 y_8^{ss} + n_3 y_9^{ss} & n_2 y_8^{sb} + n_3 y_9^{sb} & n_2 y_8^{ss'} + n_3 y_9^{ss'} & n_2 y_8^{sb'} + n_3 y_9^{sb'} \\ n_2 y_8^{bd} + n_3 y_9^{bd} & n_2 y_8^{bs} + n_3 y_9^{bs} & n_2 y_8^{bb} + n_3 y_9^{bb} & n_2 y_8^{bs'} + n_3 y_9^{bs'} & n_2 y_8^{bb'} + n_3 y_9^{bb'} \end{pmatrix}, \quad (13)$$

where we have assumed that the scalar fields  $\phi_{1,2,3}^{(\prime)}$  contained in  $\Phi_{1,2,3}^{(\prime)}$ , develop vacuum expectation values in all neutral directions:

$$\langle \phi_1^{(\prime)} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1^{(\prime)} \\ 0 \\ 0 \end{pmatrix}, \quad \langle \phi_{2,3}^{(\prime)} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ k_{2,3}^{(\prime)} \\ n_{2,3}^{(\prime)} \end{pmatrix}. \quad (14)$$

Here  $n_{1,2,3}^{(\prime)}$  characterizes the  $SU(3)_L$  breaking and  $k_{1,2,3}^{(\prime)}$  the subsequent  $SU(2)_L$  breakdown.

One can verify that a realistic pattern of quark masses and interactions can be obtained from the above mass matrices, though its detailed study is beyond the scope of the present paper. One characteristic feature which we can comment is the existence of heavy exotic quarks which, in general, mix with those of the standard model leading to an effective violation of unitarity of the CKM matrix [45, 46]. Furthermore, the presence of heavy exotic quarks may lead to a number of phenomenological implications, such as accommodating the recent diphoton anomaly [47, 48].

### B. Neutrino masses

After spontaneous symmetry breaking, one obtains a Dirac neutrino mass [10]

$$-\mathcal{L}_{\text{mass}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} y_2 k'_2 + y_3 k'_3 & \tilde{y}_2 k'_2 + \tilde{y}_3 k'_3 \\ y_2 n'_2 + y_3 n'_3 & \tilde{y}_2 n'_2 + \tilde{y}_3 n'_3 \end{pmatrix} \begin{pmatrix} S_R \\ \tilde{S}_R \end{pmatrix} + \text{h.c.}, \quad (15)$$

where  $y_{2,3}$  and  $\tilde{y}_{2,3}$  are  $3 \times 3$  Yukawa matrices and we have denoted  $S = S_{1\dots 3}$  and  $\tilde{S} = S_{4\dots 6}$ . The light neutrino masses can be readily estimated in the one family approximation which, as usual, is diagonalized by a bi-unitary transformation  $\mathcal{M}_{\text{diag}} = U_\nu^\dagger \mathcal{M} U_S$ . As can be seen, the effective light neutrino mass vanishes as the scalar vacuum expectation values  $n_{2,3}$  become large with respect to  $|k'_2 n'_3 - k'_3 n'_2|$ , very much as expected in the conventional Majorana neutrino seesaw mechanism.

Another feature is that the light neutrino become massless in the limit where the dynamical alignment parameter [10]

$$k'_2 n'_3 - k'_3 n'_2$$

approaches zero. The same holds for the up quark. Hence, in the present formulation, the same alignment yields a massless  $u$  quark, implying a tension between small neutrino masses and a realistic  $u$  quark. However, this tension is still comparable with *e.g.* the Yukawa hierarchy between the electron and the top quark in the  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  model. Moreover, for typical parameter choices, this requires an upper limit to the new scale associated to the new gauge bosons, and the need for an adequate choice of Yukawa coupling parameters in order to attain a realistic mass pattern in both quark and lepton sectors.

We conclude this section pointing out that a third interesting feature of Eq. (15) is the fact that the light neutrino mass also vanish in the limit of democratic Yukawa couplings  $y_2 = \tilde{y}_2$ ,  $y_3 = \tilde{y}_3$ . A discrete symmetry favoring this relation can be implemented in a more complete model in order to relieve the tension between the neutrino and up quark scales.

### C. Exotic instantons and $n - \bar{n}$ oscillations

In this section we discuss the possibility of inducing neutron-antineutron oscillations by exotic instanton effects generated by the action of E2-branes intersecting other physical D6-branes in our  $U(3)_c \otimes U(3)_L \otimes U(1) \otimes U(1)'$  model. Fig. 2 shows the modified setup obtained by adding an E2-brane with the following set of intersections: two with the  $U(3)_c$ -stack, two with the  $U(1)'$ -stack, and four with the  $\hat{U}(1)'$ -stack (image of  $U(1)'$ ). There are 3 different species of moduli associated with each intersection of the E2-brane and the D6-branes of the model. We denote by  $\tau^i$  those living between  $E2-U(3)_c$ ,  $\alpha$  between  $E2-\hat{U}(1)'$ , and  $\beta$  between  $E2-U(1)'$ . The effective interactions among the quarks  $U$ ,  $D$  and the moduli are given by:

$$\mathcal{L}_{eff} \sim K_f^{(1)} U_f^i \tau_i \alpha + K_{f'}^{(2)} D_{f'}^i \tau_i \beta, \quad (16)$$

where  $f$  and  $f'$  stand for the flavor indices of the corresponding fields and  $i$  is the  $U(3)_c$  index. Integrating over the moduli space associated to the D6-E2 intersections, we obtain

$$\mathcal{W}_{D6-\hat{D}6-E2} = \int d^6 \tau d^4 \beta d^2 \alpha e^{\mathcal{L}_{eff}} = \mathcal{Y} \frac{e^{-S_{E2}}}{M_S^3} \epsilon_{ijk} \epsilon_{i'j'k'} U^i D^j D^k U^{i'} D^{j'} D^{k'}, \quad (17)$$

with the flavor matrix  $\mathcal{Y}_{f_1 f_2 f_3 f_4 f_5 f_6} \equiv K_{f_1}^{(1)} K_{f_2}^{(1)} K_{f_3}^{(2)} K_{f_4}^{(2)} K_{f_5}^{(2)} K_{f_6}^{(2)}$ . As the coefficients  $K^{(1,2)}$  parametrize particular homologies of the mixed disk amplitudes, we treat them as free parameters, since our model is local. Thus, the superpotential (17) leads to an effective dimension 9 six-quark operator  $\mathcal{O}_{n\bar{n}} = (u^c d^c d^c)^2 / \mathcal{M}^5$  responsible for neutron-antineutron oscillations. The related new physics scale  $\mathcal{M}$  can be written as  $\mathcal{M}^5 = y_1^{-1} e^{+S_{E2}} M_S^3 m_{\tilde{g}}^2$ , where  $m_{\tilde{g}}$  is determined by gaugino-mediated quark-squark SUSY reductions (see [49] for example), and  $y_1 \equiv \mathcal{Y}_{111111}$ .

In terms of  $\mathcal{M}$ , the  $n - \bar{n}$  transition time (in vacuum) reads  $\tau_{n\bar{n}} \simeq \mathcal{M}^5 / \Lambda_{QCD}^6$ . The current bounds on the  $n - \bar{n}$  transition time are  $\tau_{n\bar{n}} \gtrsim 3$  yrs, constraining the new physics scale to  $\mathcal{M} \gtrsim 300$  TeV. The next generation of experiments is expected to test  $\mathcal{M} \simeq 1000$  TeV [50], an interesting scale that can be reproduced by different choices of parameters  $(y_1, e^{+S_{E2}}, M_S, m_{\tilde{g}})$ . For example, one can



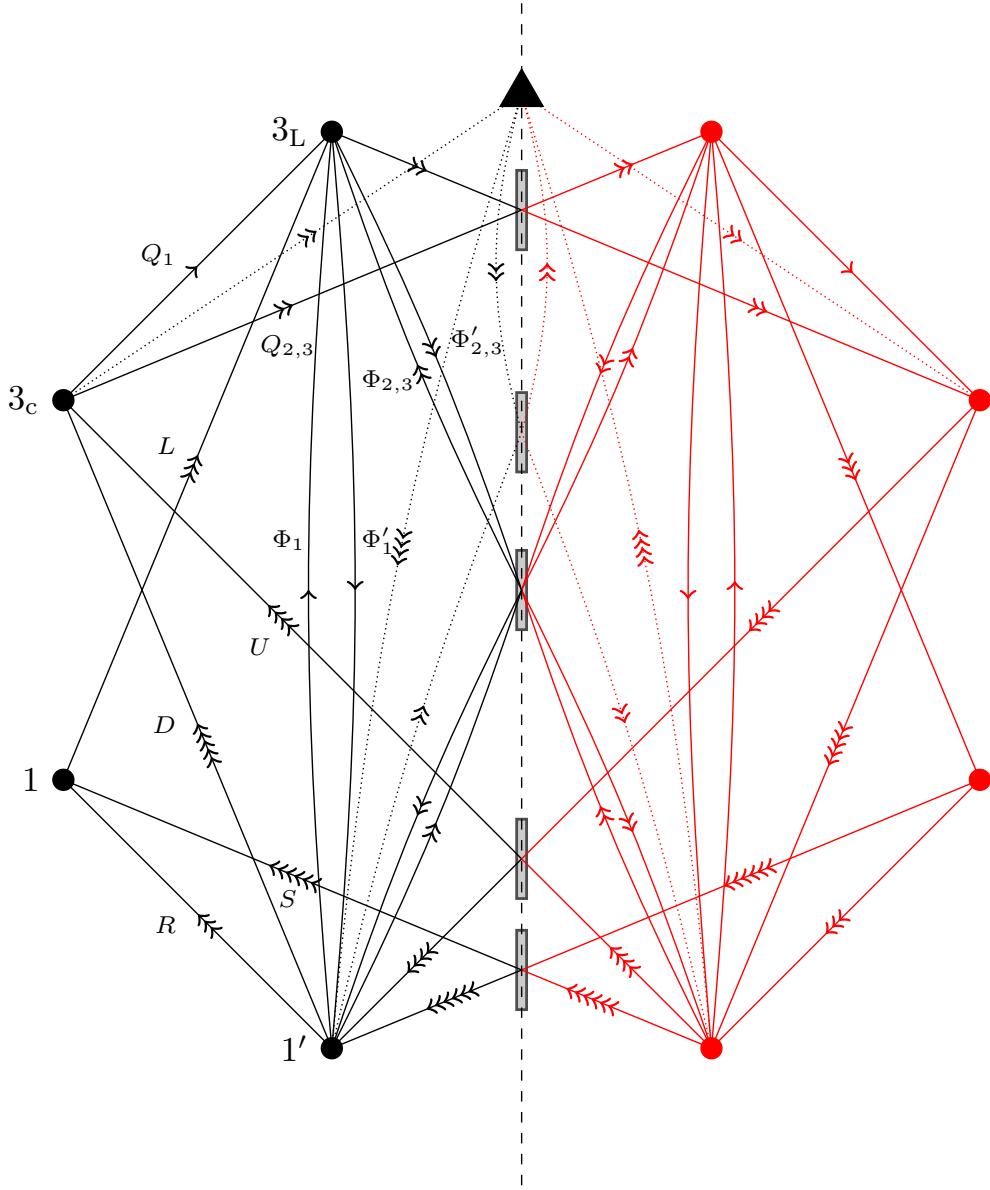


FIG. 2:  $U(3)_c \otimes U(3)_L \otimes U(1) \otimes U(1)'$  modified (un)oriented quiver theory with an intersecting E2-brane.

envisage a scenario in which  $y_1^{-1}e^{+S_{E2}} \simeq 1$ ,  $m_{\tilde{g}} \simeq 1 \text{ TeV}$ ,  $M_S \simeq 10^5 \text{ TeV}$ , compatible with TeV-scale supersymmetry and related to the naturalness of the Higgs mass. Alternatively, the same scale can be achieved by an unnatural scenario with  $m_{\tilde{g}} \simeq M_S \simeq 1000 \text{ TeV}$  ( $y_1^{-1} \simeq e^{+S_{E2}} \simeq 1$ ). In the latter case, the hierarchy problem is not solved but it is strongly alleviated by virtue of a low string scale, *i.e.* the original hierarchy of  $m_H^2/M_{Pl}^2 \simeq 10^{-34}$  is reduced to merely  $10^{-8}$ .

## V. CONCLUSIONS

In this paper, we have proposed a consistent ultra-violet completion of a standard model extension based on the gauge symmetry  $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$  within the context of an open string theory. In particular, we have constructed an example of such a 331 model in which the following properties

are satisfied in a consistent way: i) all stringy tadpoles as well as anomalous  $U(1)$ s are avoided; ii) all desired Yukawa terms are allowed at the perturbative level by open string orientations, which are in turn generated by non-perturbative effects; iii) R-parity is preserved automatically at tree-level, avoiding proton destabilization and other undesired operators; iv) Dangerous contributions to couplings of  $U(1)_X$ -RR fields cancel consistently by virtue of Eq.(8).

Even though our 331 gauge model lacks an embedding into a conventional unified field theory, we show here how it is nicely embedded in a quiver theory, free of gauge and stringy anomalies. In such construction lepton and baryon numbers are conserved at the perturbative level, so neutrinos are Dirac particles. Dynamical violation of baryon/lepton numbers can be introduced through exotic instanton effects. We have studied a particular setup for the generation of non-perturbative  $\Delta B = 2$  violating operators which would lead to neutron-antineutron oscillations and possible collider signatures. In contrast, proton decay and other dangerous R-parity violating processes are forbidden.

Finally, our quiver theory suggests the presence extra observables peculiar of string theories. For example in the context of a low scale string theory  $M_S = 10 \div 10^5$  TeV, one may have extra anomalous heavy neutral Abelian bosons, interacting through generalized Chern-Simons terms with the 331 neutral gauge bosons  $\gamma$ ,  $Z$ ,  $Z'$ ,  $X$ . In addition there is the exciting possibility of finding direct signatures of higher-spin resonances in future colliders beyond LHC.

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- [1] M. Singer, J. W. F. Valle and J. Schechter, Phys. Rev. D **22** (1980) 738. doi:10.1103/PhysRevD.22.738
  - [2] J. W. F. Valle and M. Singer, Phys. Rev. D **28** (1983) 540. doi:10.1103/PhysRevD.28.540
  - [3] R. Foot, H. N. Long and T. A. Tran, Phys. Rev. D **50** (1994) 34 doi:10.1103/PhysRevD.50.R34 [hep-ph/9402243].
  - [4] P. H. Frampton, Phys. Rev. Lett. **69** (1992) 2889. doi:10.1103/PhysRevLett.69.2889
  - [5] F. Pisano and V. Pleitez, Phys. Rev. D **46** (1992) 410 doi:10.1103/PhysRevD.46.410 [hep-ph/9206242].
  - [6] H. N. Long, Phys. Rev. D **53** (1996) 437 doi:10.1103/PhysRevD.53.437 [hep-ph/9504274].
  - [7] M. B. Tully and G. C. Joshi, Phys. Rev. D **64** (2001) 011301 doi:10.1103/PhysRevD.64.011301 [hep-ph/0011172].
  - [8] S. M. Boucenna, S. Morisi and J. W. F. Valle, Phys. Rev. D **90** (2014) no.1, 013005 doi:10.1103/PhysRevD.90.013005 [arXiv:1405.2332 [hep-ph]].
  - [9] S. M. Boucenna, R. M. Fonseca, F. Gonzalez-Canales and J. W. F. Valle, Phys. Rev. D **91** (2015) no.3, 031702 doi:10.1103/PhysRevD.91.031702 [arXiv:1411.0566 [hep-ph]].
  - [10] J. W. F. Valle and C. A. Vaquera-Araujo, Phys. Lett. B **755** (2016) 363 doi:10.1016/j.physletb.2016.02.031 [arXiv:1601.05237 [hep-ph]].
  - [11] F. F. Deppisch, N. Desai and J. W. F. Valle, Phys. Rev. D **89** (2014) no.5, 051302 doi:10.1103/PhysRevD.89.051302 [arXiv:1308.6789 [hep-ph]].

- [12] A. J. Buras, F. De Fazio and J. Girrbach-Noe, JHEP **1408** (2014) 039 doi:10.1007/JHEP08(2014)039 [arXiv:1405.3850 [hep-ph]].
- [13] S. M. Boucenna, J. W. F. Valle and A. Vicente, Phys. Rev. D **92** (2015) no.5, 053001 doi:10.1103/PhysRevD.92.053001 [arXiv:1502.07546 [hep-ph]].
- [14] A. Sagnotti, IN \*CARGESE 1987, PROCEEDINGS, NONPERTURBATIVE QUANTUM FIELD THEORY\* 521-528 AND ROME II UNIV. - ROM2F-87-025 (87,REC.MAR.88) 12p [hep-th/0208020].
- [15] G. Pradisi and A. Sagnotti, Phys. Lett. B **216** (1989) 59. doi:10.1016/0370-2693(89)91369-5
- [16] M. Bianchi and A. Sagnotti, Phys. Lett. B **247** (1990) 517. doi:10.1016/0370-2693(90)91894-H
- [17] M. Bianchi and A. Sagnotti, Nucl. Phys. B **361** (1991) 519. doi:10.1016/0550-3213(91)90271-X
- [18] M. Bianchi, G. Pradisi and A. Sagnotti, Nucl. Phys. B **376** (1992) 365. doi:10.1016/0550-3213(92)90129-Y
- [19] C. Angelantonj, M. Bianchi, G. Pradisi, A. Sagnotti and Y. S. Stanev, Phys. Lett. B **385** (1996) 96 doi:10.1016/0370-2693(96)00869-6 [hep-th/9606169].
- [20] C. Angelantonj, M. Bianchi, G. Pradisi, A. Sagnotti and Y. S. Stanev, Phys. Lett. B **387** (1996) 743 doi:10.1016/0370-2693(96)01124-0 [hep-th/9607229].
- [21] M. Bianchi, G. Inverso, J. F. Morales and D. R. Pacifici, JHEP **1401** (2014) 128 doi:10.1007/JHEP01(2014)128 [arXiv:1307.0466 [hep-th]].
- [22] C. Coriano, N. Irges and E. Kiritsis, Nucl. Phys. B **746** (2006) 77 doi:10.1016/j.nuclphysb.2006.04.009 [hep-ph/0510332].
- [23] P. Anastasopoulos, M. Bianchi, E. Dudas and E. Kiritsis, JHEP **0611** (2006) 057 doi:10.1088/1126-6708/2006/11/057 [hep-th/0605225].
- [24] P. Anastasopoulos, F. Fucito, A. Lionetto, G. Pradisi, A. Racioppi and Y. S. Stanev, Phys. Rev. D **78** (2008) 085014 doi:10.1103/PhysRevD.78.085014 [arXiv:0804.1156 [hep-th]].
- [25] M. Bianchi and M. Samsonyan, Int. J. Mod. Phys. A **24** (2009) 5737 doi:10.1142/S0217751X09048022 [arXiv:0909.2173 [hep-th]].
- [26] M. Bianchi and G. Inverso, Fortsch. Phys. **60** (2012) 822 doi:10.1002/prop.201200047 [arXiv:1202.6508 [hep-th]].
- [27] L. E. Ibanez and A. M. Uranga, JHEP **0703** (2007) 052 doi:10.1088/1126-6708/2007/03/052 [hep-th/0609213].
- [28] L. E. Ibanez, A. N. Schellekens and A. M. Uranga, JHEP **0706** (2007) 011 doi:10.1088/1126-6708/2007/06/011 [arXiv:0704.1079 [hep-th]].
- [29] R. Blumenhagen, M. Cvetič and T. Weigand, Nucl. Phys. B **771** (2007) 113 doi:10.1016/j.nuclphysb.2007.02.016 [hep-th/0609191].
- [30] M. Cvetič, R. Richter and T. Weigand, AIP Conf. Proc. **939** (2007) 227. doi:10.1063/1.2803809
- [31] M. Cvetič, R. Richter and T. Weigand, Phys. Rev. D **76** (2007) 086002 doi:10.1103/PhysRevD.76.086002 [hep-th/0703028].
- [32] A. Addazi and M. Bianchi, JHEP **1412** (2014) 089 doi:10.1007/JHEP12(2014)089 [arXiv:1407.2897 [hep-ph]].
- [33] A. Addazi, JHEP **1504** (2015) 153 doi:10.1007/JHEP04(2015)153 [arXiv:1501.04660 [hep-ph]].
- [34] A. Addazi and M. Bianchi, JHEP **1507** (2015) 144 doi:10.1007/JHEP07(2015)144 [arXiv:1502.01531 [hep-ph]].
- [35] A. Addazi and M. Bianchi, JHEP **1506** (2015) 012 doi:10.1007/JHEP06(2015)012 [arXiv:1502.08041 [hep-ph]].
- [36] A. Addazi, arXiv:1505.00625 [hep-ph].
- [37] A. Addazi, arXiv:1505.02080 [hep-ph].
- [38] A. Addazi, arXiv:1506.06351 [hep-ph].
- [39] A. Addazi, M. Bianchi and G. Ricciardi, JHEP **1602** (2016) 035 doi:10.1007/JHEP02(2016)035 [arXiv:1510.00243 [hep-ph]].
- [40] E. C. G. Stueckelberg, Helv. Phys. Acta **11** (1938) 225. doi:10.5169/seals-110852

- [41] R. N. Mohapatra and J. W. F. Valle, Phys. Lett. B **177** (1986) 47. doi:10.1016/0370-2693(86)90011-0
- [42] G. Aldazabal, S. Franco, L. E. Ibanez, R. Rabadan and A. M. Uranga, J. Math. Phys. **42** (2001) 3103 doi:10.1063/1.1376157 [hep-th/0011073].
- [43] M. Cvetič, J. Halverson and R. Richter, JHEP **0912** (2009) 063 doi:10.1088/1126-6708/2009/12/063 [arXiv:0905.3379 [hep-th]].
- [44] M. Cvetič, J. Halverson and P. Langacker, JHEP **1111** (2011) 058 doi:10.1007/JHEP11(2011)058 [arXiv:1108.5187 [hep-ph]].
- [45] F. J. Botella, G. C. Branco and M. Nebot, Phys. Rev. D **79** (2009) 096009 doi:10.1103/PhysRevD.79.096009 [arXiv:0805.3995 [hep-ph]].
- [46] S. Morisi, M. Nebot, K. M. Patel, E. Peinado and J. W. F. Valle, Phys. Rev. D **88** (2013) 036001 doi:10.1103/PhysRevD.88.036001 [arXiv:1303.4394 [hep-ph]].
- [47] S. M. Boucenna, S. Morisi and A. Vicente, arXiv:1512.06878 [hep-ph].
- [48] P. V. Dong and N. T. K. Ngan, arXiv:1512.09073 [hep-ph].
- [49] A. Addazi, arXiv:1510.02911 [hep-ph].
- [50] D. G. Phillips, II *et al.*, Phys. Rept. **612** (2016) 1 doi:10.1016/j.physrep.2015.11.001 [arXiv:1410.1100 [hep-ex]].